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14. ABSTRACT The purpose of this investigation was to improve the understanding of the way that sound in water interacts with various types of targets in situations similar to those encountered in underwater acoustics. The emphasis was on situations relevant to the use of sonar systems in shallow water. Laboratory methods were developed and tested for displaying the scattering of sound, including partially-exposed targets. Some of the work concerned bistatic scattering. Much of the research was in the intermediate frequency range where geometrically motivated ray based methods were helpful even when elastic responses were significant. Signal processing methods used included synthetic aperture sonar and line-scan supersonic acoustic holography. Some of the research concerns the scattering by beams of sound including vortex beams.						
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December 2014

Novel Acoustic Scattering Processes for Target Discrimination

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I. Summary: The purpose of this investigation was to improve the understanding of the way that sound in water interacts with various types of targets in situations similar to those encountered in underwater acoustics. The emphasis was on situations relevant to the use of sonar systems in shallow water. Laboratory methods were developed and tested for displaying the scattering of sound, including partially-exposed targets. Some of the work concerned bistatic scattering. Much of the research was in the intermediate frequency range where geometrically motivated ray based methods were helpful even when elastic responses were significant. Signal processing methods used included synthetic aperture sonar and line-scan supersonic acoustic holography. Some of the research concerns the scattering by beams of sound including vortex beams.

II. Introduction and Organization of this Report: The majority of resources were used to support the activities of graduate students. The simplest way of summarizing the research was to compile in sequence edited versions of the Annual Reports submitted to ONR for FFY 2010, 2011, 2012, 2013, and 2014. (Note, however, because of the depletion of grant funds the work in the report covering FFY 2014 was supported significantly by a different ONR grant.) In this Final Report these Annual Reports are followed by the abstracts of two Ph.D. dissertations primarily funded by this grant.

III. Refereed Publications Subsequent to FFY 2014 report:

1. L. Zhang and P. L. Marston, "Acoustic radiation torque on small objects in viscous fluids and connection with viscous dissipation," J. Acoust. Soc. Am. 136, 2917-2921 (2014).
2. D. S. Plotnick, P. L. Marston, K. L. Williams, and A. L. España, "High frequency backscattering by a solid cylinder with axis tilted relative to a nearby horizontal surface," J. Acoust. Soc. Am. 137, 470-480 (2015).
3. P. L. Marston, "Surprises and anomalies in acoustical and optical scattering and radiation forces," Journal of Quantitative Spectroscopy and Radiative Transfer (accepted).

IV. Annual Reports: Note: Editing includes the removal of redundant or obsolete information.

Novel Acoustic Scattering Processes for Target Discrimination (2010)

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Award Number: N000140410075 and N000141010093
<http://www.physics.wsu.edu/People/People-Faculty.html>

LONG TERM GOALS

The grant that expired during FY10 (N000140410075) was part of the Shallow-Water Autonomous Sensing Initiative to improve the reliability of acoustic methods using a wide frequency range and scattering data not necessarily limited to monostatic signatures. The related follow-on grant (N000141010093) that started in mid-FY10 has similar goals.

OBJECTIVES

The objective of these grants is to improve the understanding of acoustic scattering processes relevant to man-made objects in the shallow water environment. The current emphasis is on the interpretation of the effects on signatures of placing objects close to an interface. Synthetic aperture sonar, acoustic holographic images, spectral properties of scattering, and bistatic scattering are also examined. Other objectives involve improved understanding and modeling of scattering mechanisms.

APPROACH

A multifaceted research approach appears to be advisable because some acoustic strategies may not *always* be applicable and different strategies may require widely different amounts of time to acquire data for a region of interest. Consequently it appeared to Marston that this project should retain research concerning both low frequency and high frequency sonar technologies. Beginning in FY07, the experimental effort at WSU was shifted to emphasize scaled targets directly relevant to the planning and interpretation of experiments carried out at the NSWC-PCD pond in cooperation with UW-APL. Thus, as explained in the Reports for FY07-09 [1-3], measurements at WSU were extended to include bistatic and monostatic acoustic properties of solid aluminum cylinders in the free field and adjacent to interfaces. This kind of target was selected because experiments at the NSWC pond have used aluminum cylinders of various dimensions. Furthermore, scattering by an aluminum cylinder has become a test case for development of finite element methods for the evaluation of both free-field scattering and scattering by targets adjacent to an interface [4,5]. In support of those efforts the experiments at WSU have been concerned with frequency domain (“acoustic color”) displays of the scattering as well as time domain and spatial SAS and holographic imaging displays. Beginning in FY08, measurements in the scattering by tilted

aluminum cylinders were extended over a wider range of scaled frequencies by fabricating targets that were small in size. We demonstrated at WSU that elastic modes of tilted aluminum cylinders produce strong scattering for a wide ka range. Measurements of the scattering from aluminum cylinders with ka from 10 to 30 show prominent features in the scattering associated with elastic waves guided by the surface of the cylinder. Those features would not be present if it were possible to replace the cylinder by a rigid cylinder and may be referred to as elastic glints. In addition to understanding scattering effects associated with the elastic response of the target and modifications of the scattering associated with the proximity to an interface, the research during FY08 and 09 was extended to examine the potential advantages of bistatic scattering associated with simple specular reflection from the outside of various targets having a vertical symmetry axis. New phenomena examined during FY10 are emphasized in this report.

Professor P. L. Marston directs the research. During FY10 the graduate students supported at least in part by this grant are listed below together with the nature of their research. These students were: J. R. La Follett (scattering experiments with cylinders and other shapes near flat surfaces); A. R. Smith (elastic features visible in SAS imaging); and G. Eastland (scattering by metallic cylinders near flat surfaces). With partial support from this grant, Samantha Damiano (an EE major) has been upgrading our software. Postdoctoral contributors to this effort in FY10 are listed as follows: Dr. T. Marston (a wide range of experiments including SAS imaging, signal processing, and experiment design and fabrication) and Dr. D. B. Thiessen (experiment design, FEM computations and oversight tasks). T. Marston has a Ph. D. in acoustics from Penn State Univ. Thiessen is a WSU Research-Faculty member. J. R. La Follett completed his Ph.D. [6] and both La Follett and T. Marston are currently employed at NSWC-PCD. A prior student Baik [7] is now a postdoc at Woods Hole Oceanographic Institution.

WORK COMPLETED

During FY10, in addition to La Follett's thesis [6] a publication appeared based primarily on collaborations with UW-APL and NSWC-PCD [5] and various papers using Dr. T. Marston's reversible method of SAS processing (the development of which was partly supported by this grant) were submitted and published and presented at *IEEE Oceans* [8-11]. Selected aspects of our research were presented at meetings of the *Acoustical Society of America* [12-20]. With the partial support of this grant T. Marston and P. Marston helped with NSWC-PCD pond experiments in March 2010.

RESULTS

(1) Acoustic backscattering enhancement for tilted solid cylinders adjacent-to or breaking-through a free surface: During FY10 La Follett discovered a new type of backscattering enhancement relevant to mid- ka scattering by horizontal cylinders in close proximity to a free surface or breaking-through a free surface [6]. This may be relevant to the detection of certain classes of threats. In La Follett's experiment the backscattering was measured with grazing incidence sound (with the grazing angle held near 20 degrees) as the azimuthal angle was spun from 0 to 90 degrees. A solid aluminum cylinder was used for which the free-field scattering mechanisms are well understood in the ka range

of the experiment. A plot of the time dependence of the scattering in response to a short pulse is shown in **Figure 1**. The surprising result is the uniform brightness and magnitude of the late arc that is especially visible between 35 and 65 degrees. (Here 0 degrees designates broadside orientation while 90 degrees designates end-on.) Most of the bright features away from 0 degrees and 90 degrees are associated with known elastic coupling mechanisms [5-7]; however, the slowly varying intensity of the late bright arc strongly suggests that it is not associated with the elasticity of the cylinder. Additional measurements were taken of backscattering as a function of the vertical position of the cylinder at fixed azimuth for selected values between 35 and 65 degrees. Those measurements indicate that the brightness and the timing of the late arc depends on the separation of the crest of the cylinder from the free surface such that the enhancement is greatly diminished in amplitude if the separation is greater than about 6 mm. The cylinder diameter was 63.5 mm and length 190.5 mm and the spectral frequency of the incident burst was about 220 kHz. The enhancement is still present when the crest of the cylinder is raised above the free surface. The most plausible explanation is that an acoustic wave in water is partially guided near the smooth crest of the cylinder and is partially reversed at the abrupt truncation at the end of the cylinder. From reciprocity (as well as consideration of the wave-vector components) the reversed wave sheds energy back towards the source of sound. The guiding is thwarted when the gap is too large since in that case the acoustic wave can make it over the crest of the gap since the associated angular waveguide is not cut-off. While estimates of the cut-off condition are of the proper magnitude to explain aspects of the observations, additional research is needed, some of which is underway by one of the current graduate students (Smith).

(2) Evolution of the backscattering by proud tilted solid cylinders adjacent to a free surface (elastic features): During FY10 La Follett discovered and modeled additional elastic backscattering enhancements relevant to mid- ka backscattering by horizontal metallic cylinders adjacent to or breaking through a free surface [6]. The evolution of the coupling of sound to elastic mechanisms is relevant to viewing proud or partially buried metallic cylinders at grazing incidence. This is a significant extension of prior work noted in reports [2,3], in La Follett's thesis and Baik's publication [21] on the evolution of specular features. In La Follett's research the elastic features may be interpreted from geometrical consideration of the ways that acoustic waves couple to guided elastic modes of the cylinder. Placing the cylinder proud on a flat surface usually introduces additional ways for acoustic waves to couple to guided elastic modes of the cylinder. One approach is to view the evolution of features in either the time or the frequency domain as a function of either the tilt angle or the cylinder or the distance from the interface. La Follett's observations of this type during FY2010 viewed at grazing incidence (20 degrees) a solid aluminum cylinder. His geometric models were especially important for understanding the relevance of surface proximity to the excitation of helical and face crossing rays associated with Rayleigh waves on the cylinder. Perhaps the most important result is the discovery that proximity to a flat surface significantly extends the range of tilt angles over which helical rays can contribute to the backscattering [6]. The extension is a consequence of reflection of sound from the adjacent flat surface. A ray model shows the extension is especially important for short cylinders. This is relevant to the interpretation of scattering by an aluminum cylinder having an aspect ratio $L/D = 2$

proud on sand obtained at the NSWC pond facility [5]. The extension of tilt angles for helical ray coupling will also apply to guided waves on cylindrical shells.

(3) Laboratory backscattering measurements and pressure gradient related coupling to elastic modes in preparation for NSWC-PCD pond scattering experiments: Dr. Tim Marston did a series of experiments supported by this grant in preparation for NSWC-PCD pond experiments that were carried out during March and April of 2010. These were generally of two types: (a) As explained in the report for FY09, measuring the evolution of the backscattering as a function of target distance below a free surface and frequency is useful for classifying the symmetry of the excited target mode. In the case of cylinders the tilt angle of the cylinder is an additional variable; the grazing angle is generally held fixed. Grazing incidence and the adjacent free surface produces a vertical standing wave component to the incident wave and for small horizontal cylinders the coupling is generally maximized with the axis either on pressure anti-nodes (for “pressure coupled” modes) or on pressure nodes (for “gradient coupled” modes). Tim took measurements of this type for a variety of small cylinders. We selected one of the aluminum cylinders with a flat paddle on the end for enhanced coupling for fabrication at WSU of a scaled-up version. This cylinder was deployed at the NSWC-PCD pond and is the third shape from the left side of Fig. 1 of [10]. One important result is that some of the modes visible on the small cylinder at WSU were also visible in the scaled proud cylinder in the NSWC-PCD pond experiment. (b) Tim carried out a series of relevant measurements of backscattering as a function of tilt angle for an open-ended water-filled aluminum cylindrical shell scaled to one deployed at the NSWC-PCD pond [11] with an aspect ratio Length/Diameter = $L/D = 2$. One of his important results is that when the shell is hung proud close to a free surface and viewed with grazing angle of 20 degrees, the evolution of the response spectrum as a function of tilt angle is very similar to the case in which the cylinder is hung adjacent to a flat floating platform of closed-cell extruded polystyrene foam (“StyrofoamTM”). This method of simulating scattering by objects near an air-water surface was subsequently deployed at the NSWC-PCD pond.

(4) Development of reversible SAS, CSAS, and line-scan holographic processing methods: During FY10 until his departure for NSWC-PCD in August 2010, a significant fraction of Tim Marston’s time went into the development of reversible synthetic aperture sonar (SAS), circular SAS (CSAS), and line-scan holographic processing methods. Some resources from this grant were used to support this work along with resources from other ONR grants to P. Marston’s program at WSU [22]. The reversibility of the processing is useful since it facilitates the extraction of the portion of a recorded signature contributing to a specified portion of a SAS, CSAS, or holographic images. That is achieved by introducing a suitably located spatial filter. Applications demonstrated to date include: (a) the extraction of the spectral features associated with a specific portion of an image [8,11]; (b) in tank experiments extraction of target responses from data that also includes reverberation from sufficiently distant boundaries of the tank [8]; (c) in NSWC-PCD pond data extraction of target responses from line-scan data in which other targets are also viewed during same line-scan [10,11]; and (d) verification of the cause of certain feature loci when a broadside aluminum cylinder is lowered below a free surface with fixed grazing angle illumination and a vertically scanned bistatic SAS receiver (in work

done with Eastland [9]). In addition to these applications one of the current students (Smith) has displayed large elastic features in CSAS images for metallic objects.

IMPACT/APPLICATIONS

La Follett's research on the scattering by cylinder close-to, or breaking through, a free surface has plausible implications for the identification of certain types of threats. Tim Marston's experiments on mode classification of small objects placed close to a free surface also has plausible implications for the identification of other types of threats. The SAS processing methods have broader applications to data acquisition and object identification. T. Marston and P. Marston helped with NSWC-PCD pond experiments (research not shown here) in March 2010.

TRANSITIONS

Dr. Jon R. La Follett, whose thesis work was primarily supported by this grant, is currently employed in acoustics research on the staff of NSWC-PCD. Dr. Timothy M. Marston, who was partially supported by this grant during FY10, is now employed there also. One of his methods for the spatial filtering of line SAS data was immediately applied to data acquired at NSWC-PCD in March 2010 [8,10,11].

RELATED PROJECTS

Some of this work was in cooperation with UW-APL and NSWC-PCD. Up to the time of his departure for NSWC-PCD, during FY10 Dr. Timothy Marston's work was jointly supported by some other ONR grants: N000140810024 and N000140910612.

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PUBLICATIONS

J. R. La Follett, *Boundary Effects On The Scattering Of Sound By Elastic Objects Under Water* (Ph. D. Thesis, Washington State University, Pullman, WA, August 2010).

K. L. Williams, S. G. Kargl, E. I. Thorsos, D. S. Burnett, J. L. Lopes, M. Zampolli, and P. L. Marston, “Acoustic Scattering from a solid aluminum cylinder in contact with a sand sediment: Measurements, modeling and interpretation,” *J. Acoust. Soc. Am.* 127, 3356-3371 (2010) [refereed].

G. C. Eastland, T. M. Marston, and P. L. Marston, “Evolution of Acoustic Feature Timing and Imaging for Different Cylinder Exposures and Applications of Reversible SAS Filtering,” *Proceedings of the OCEANS 2010 MTS/IEEE SEATTLE Conference*, IEEE Catalog Number: CFP10OCE-CDR, ISBN: 978-1-4244-4333-8 (2010), 4 pages.

T. M. Marston, P. L. Marston, and K. L. Williams, “Scattering resonances, filtering with reversible SAS processing, and applications of quantitative ray theory,” *Proceedings of the OCEANS 2010 MTS/IEEE SEATTLE Conference*, IEEE Catalog Number: CFP10OCE-CDR, ISBN: 978-1-4244-4333-8 (2010), 9 pages.

S. G. Kargl, K. L. Williams, T. M. Marston, J. L. Kennedy, and J. L. Lopes, “Acoustic Response of Unexploded Ordnance (UXO) and Cylindrical Targets,” *Proceedings of the OCEANS 2010 MTS/IEEE SEATTLE Conference*, IEEE Catalog Number: CFP10OCE-CDR, ISBN: 978-1-4244-4333-8 (2010), 5 pages.

A. L. Espana, K. L. Williams, S. G. Kargl, M. Zampolli, T. M. Marston, and P. L. Marston, "Measurements and Modeling of the Acoustic Scattering from an Aluminum Pipe in the Free Field and in Contact with a Sand Sediment," *Proceedings of the OCEANS 2010 MTS/IEEE SEATTLE Conference*, IEEE Catalog Number: CFP10OCE-CDR, ISBN: 978-1-4244-4333-8 (2010), 5 pages.

HONORS/AWARDS/PRIZES

Second Best Student Paper in Underwater Acoustics Award (October 2009 ASA San Antonio meeting) for J. La Follett's presentation of: "Bistatic line-scan holography of scattering by metallic objects near a free surface."

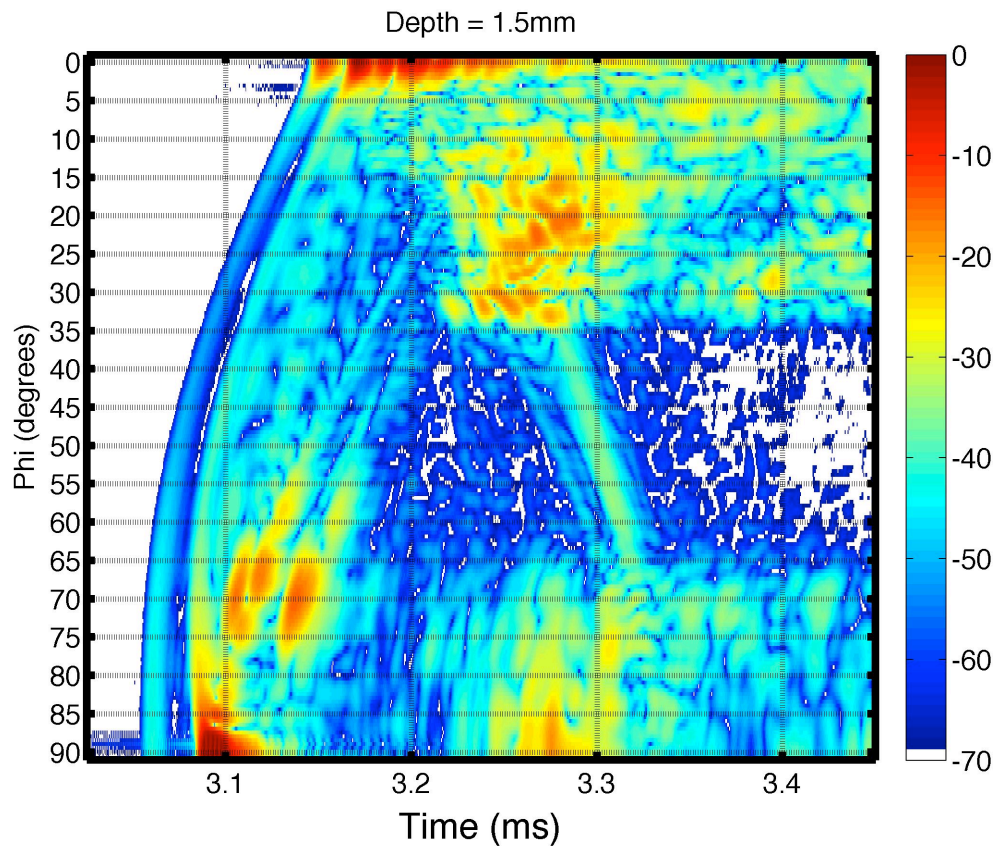


Figure 1. The figure shows the evolution of time-domain backscattering for a solid aluminum horizontal cylinder for a range of azimuthal tilt angles. The cylinder is placed with the top of the cylinder 1.5 mm below a free surface. The illumination is at a grazing angle of 20 degrees. The vertical axis is the azimuthal tilt angle Φ where 0 degrees is broadside illumination and one end is toward the source at 90 degrees. The horizontal axis is time. The late bright echo isolated from other features between about 35 and 65 degrees is a feature that is enhanced by proximity of the cylinder to a free surface. The enhancement remains even when the cylinder is raised so as to contact the free surface but it is significantly reduced for a sufficiently deep cylinder.

Novel Acoustic Scattering Processes for Target Discrimination (2011)

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LONG TERM GOALS

This grant is part of the Shallow-Water Autonomous Sensing Initiative to improve the reliability of acoustic methods using a wide frequency range and scattering data not necessarily limited to monostatic signatures.

OBJECTIVES

The objective of this grant is to improve the understanding of acoustic scattering processes relevant to man-made objects in the shallow water environment. The current emphasis is on the interpretation of the effects on signatures of placing objects close to an interface. Synthetic aperture sonar, acoustic holographic images, spectral properties of scattering, and bistatic scattering are also examined. Other objectives involve improved understanding and modeling of scattering mechanisms.

APPROACH

A multifaceted research approach appears to be advisable because some acoustic strategies may not *always* be applicable and different strategies may require widely different amounts of time to acquire data for a region of interest. Consequently it appeared to Marston that this project should retain research concerning both low frequency and high frequency sonar technologies. Beginning in FY07, the experimental effort at WSU was shifted to emphasize scaled targets directly relevant to the planning and interpretation of experiments carried out at NSWC-PCD in cooperation with UW-APL. Thus, as explained in the prior reports [1], measurements at WSU were extended to include bistatic and monostatic acoustic properties of solid aluminum cylinders in the free field and adjacent to interfaces. This kind of target was selected because experiments at the NSWC pond have used aluminum cylinders and other objects of various dimensions. Furthermore, scattering by an aluminum cylinder has become a test case for development of finite element methods for the evaluation of both free-field scattering and scattering by targets adjacent to an interface [2-5]. In support of those efforts the experiments at WSU have been concerned with frequency domain ("acoustic color") displays of the scattering as well as time domain and spatial bistatic SAS and holographic imaging displays [4-6]. The features investigated include those that would not be present if it were possible to replace the target by a rigid object. Such features may be referred to as elastic glints.

During FY10 the approaches were broadened to include tests involving inverse imaging based on reversible line-scan SAS (RSAS), reversible circular SAS (RCSAS), and reversible line-scan bistatic quasi-holographic imaging [7-9]. The reversible aspect of these methods makes it feasible to extract the signals and spectral content associated a designated region of an image. Among other applications this technique makes it possible to test hypotheses concerning the cause of certain image features. New phenomena examined during FY11 (or late in FY10) are emphasized in this report.

Theoretical components of the research include extensions of prior modeling of scattering amplitudes of objects viewed at grazing incidence [10] and the analysis of aspects of the scattering of acoustic beams by simple objects [11-13].

Professor P. L. Marston directs the research. During FY11 the graduate students supported at least in part by this grant are listed below together with the nature of their research. These students were: A. R. Smith (elastic features visible in SAS imaging); G. Eastland (scattering by metallic cylinders near flat surfaces and SAS imaging); and M. Terrazas (experiment setup with partial support from this grant during summer 2011). With partial support from this grant, Samantha Damiano (an EE major who graduated in May 2011) worked on improving our software. Dr. D. B. Thiessen, a WSU Research-Faculty member assisted with experiment design, FEM computations and occasional oversight tasks. Drs. T. Marston and J. R. La Follett [4] are researchers who departed during FY10 who are currently employed at NSWC-PCD and remain involved in related research. Dr. Baik [5] is currently a postdoc at Woods Hole Oceanographic Institution.

WORK COMPLETED

During FY11 various publications appeared or were submitted supported partially by this grant [4, 6, 11-13]. A paper was submitted to *IEEE Oceans 2011* containing processed data acquired at WSU during FY10 [9]. Work from collaboration on scattering that includes P. Marston was also submitted [14]. Other selected aspects of the research were presented at meetings of the *Acoustical Society of America* [15-25]. With support from this grant P. Marston helped in research at NSWC-PCD in March and April 2011.

RESULTS

(1) Bistatic scattering by solid cylinders adjacent-to or breaking-through a free surface and applications of line-scan reversible SAS processing methods: In this experiment a horizontal cylinder is illuminated with a short pulse at a fixed grazing angle. During FY11 Eastland extended his prior investigation [26] of bistatic scattering by a solid aluminum cylinder close to a free surface. Some of the methods used in the investigation involve the display of the timing loci of scattering features as one of the geometric parameters is changed. In this type of plot the parameters changed are either the position of the cylinder relative to the free surface or the location of the hydrophone. For a fixed hydrophone position in the far field the rate of change of feature timing reveals the number sequence of the interactions with the adjacent flat surface for a given feature. Comparison with feature evolution in the two types of plots (fixed hydrophone and fixed target) allows the rapid identification of features in the other type of plot. In addition the interaction sequence for a given feature type was identified using reversible line-scan

SAS imaging so as to extract the signal loci associated with a given image feature according to which side of the interface the selected feature appeared [17]. In the extended work it was also possible for Eastland to identify specific loci and image features associated with multiple scattering in which the associated wave reflected from the curved surface of the cylinder more than one time. While Eastland's emphasis has been on specular reflection features in the mid-ka region, he has also been able to identify the cause of some of the elastic features visible in the SAS images and in the feature loci. He has also calculated the relative timing of the bistatic specular features for the case of sources and receivers in the far field. See **Figure 1**.

(2) Feature identification and extraction for non-axisymmetric (square and rectangular) cylinders and related studies of the evolution of acoustic spectra: Circular cylinders are axisymmetric and the associated symmetry facilitates the evaluation of the scattering by the method of finite elements. Even for moderately high ka (for example ka of 30), our prior investigations show that typical metallic circular cylinders reveal elastic responses along with specular reflections and edge diffraction [2-5]. What if the metallic cylinder is a square or rectangular cylinder instead of a circular cylinder? Is there still a significant elastic response at moderately high frequencies? A. R. Smith has been investigating the response of solid-square and rectangular metal cylinders with assistance from D. Zartman and D. Plotnick (supported by other ONR grants) and prior assistance from T. Marston [24]. The measurements reveal regular elastic features identifiable in the backscattering in CSAS images as well in plots of the "acoustic color" (the response spectrum as a function of the orientation of the target). Many of the elastic responses are identifiable as leaky waveguide modes of the target. Reversible CSAS (RCSAS) processing was used to relate image features to the features in the response spectrum.

(3) Testing of a reversible line scan SAS system: During summer of 2011, Smith and Terrazas assisted Plotnick and Zartman in the testing of a laboratory based line scan SAS system useful over a different frequency range than our prior system.

(4) Modeling of scattering amplitudes for cylindrical targets and the dependence on grazing angle: At various times during FY11, P. Marston made progress in the modeling and identification of physical processes relevant to the scattering of circular cylinders. Some of the aspects included the topics listed here. (a) Some mid-frequency waveguide modes of metallic and plastic solid cylinders and water-filled metallic cylindrical shells were modeled and identified [21]. In aspects of that work Dr. Thiessen (of WSU) assisted as well as Dr. Espana (of APL-University of Washington). (b) More importantly a simple physical model was proposed for the backscattering by a circular cylinder situated adjacent to a flat free surface (a pressure-release surface) viewed broadside at a small grazing angle. The model combines aspects of the analysis in [3,4] and [10]. The important result is that there is a significant reduction of the low frequency response at small grazing angles. This result is also consistent with the predictions of the exact expression for the backscattering by an infinitely long rigid cylinder placed halfway through a free surface reviewed by Baik and Marston [10]. A geometric analysis was also developed for the suppression of certain modes in that case of certain grazing angles. That analysis is roughly analogous to one developed by Marston to understand mode

coupling in a different context [11,19]. (c) Previously Baik and Marston [10] evaluated the backscattering by an infinitely long rigid cylinder viewed at grazing incidence and placed part-of-the-way through a free surface by analytically evaluating the Kirchhoff approximation. During FY11 Marston found that the required integrals could be rapidly evaluated using numerical integration. The method was confirmed by comparison with the prior analytical result [10] and by comparison with the aforementioned exact solution. Even though the investigations in (b) and (c) pertain directly to a rigid cylinders at or near a free surface, there are reasons to believe some aspects of the results are relevant to understanding the response of some elastic targets and some targets near other types of surfaces. La Follett discussed some relevant experiments in the intermediate frequency range [3,4].

(5) Modeling of the scattering by spheres in acoustic beams: During FY11 Marston made significant progress in modeling and understanding of the scattering of sound by spheres placed on the axis of acoustic beams [11-13]. The most recent research [13] concerns the analysis of the asymmetry in the scattering by such a sphere for the case of a Bessel beam and the significance of the asymmetry to understanding the acoustic radiation forces.

(6) Time reversal measurements for simple targets in the presence of clutter: During FY11 we performed laboratory experiments at WSU on the influence of clutter on mode detection for simple resonant targets in the presence of non-resonant scatterers that served as a source of clutter. Iterative time reversal was successful in pulling out modes in the presence of clutter. Since those experiments were done in cooperation with ONR supported researchers at other facilities, that research will be reported elsewhere.

(7) Circular cylinder with a paddle for FEM code verification: During FY10 an aluminum circular cylinder with a flat paddle on the end was fabricated with support from this grant and some modes were identified for a scaled version [1]. This is a non-axisymmetric target. During FY11 the large version was loaned to NSWC and used in addition tests.

IMPACT/APPLICATIONS

The SAS and CSAS processing methods have broader applications to data acquisition and object identification. The scattering by objects placed close to a free surface also has plausible implications for understanding other situations of interest. The measured scattering properties of non-axisymmetric targets will eventually find application in the testing of robust FEM scattering codes. Drs. T. Marston and J. La Follett have been (or are presently) examining applications at NSWC-PCD of some of the methods developed previously at WSU and/or some of the phenomena previously investigated. Some of the processing methods have been applied to data acquired at NSWC-PCD.

TRANSITIONS

S. Damiano, the EE major who assisted with code development for data acquisition during FY11, after completing her degree became employed in the electric power industry.

RELATED PROJECTS

Some of this work was in cooperation with UW-APL and NSWC-PCD.

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HONORS/AWARDS/PRIZES

P. L. Marston was advanced to Senior Member status in the Optical Society of America.

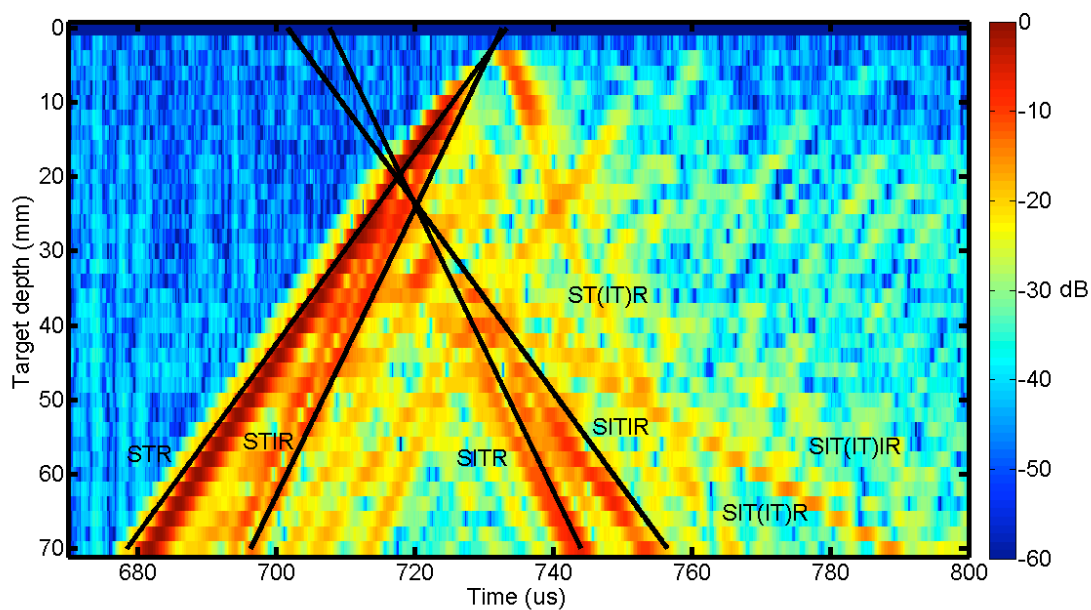


Figure 1. Grazing bistatic transient response of an aluminum cylinder as a function of target offset relative to the free surface. The cylinder is lowered through the free surface as the broadside bistatic scattering is monitored at a fixed location. The illumination is a two-cycle tone burst at 480 kHz and the cylinder diameter is 25.4 mm. This record is for a case where the incident grazing angle greatly exceeds the receiver-grazing angle. The dark horizontal band at the top is present because the cylinder has not yet contacted the flat interface. As the cylinder is lowered more of it becomes exposed to the incident sound. The solid lines STR, STIR, SITR, & SITIR are the calculated absolute single-scattering specular reflection loci based on a far-field scattering approximation. The labels indicate the sequence of the reflections in going from the source to the receiver. (Key: S = source, T = target, R = receiver, I = interface.) For example, at the beginning SIT means the acoustic wave reflected from the flat interface prior to being scattered by the cylinder. The observed STIR specular locus contains a noticeable precursor attributable to the elastic response of the cylinder. Multiple scattering loci STITR and SITITR are easily visible near the right and they also have the predicted slopes. The identities of several loci were also verified using reversible SAS processing and image masks to isolate contributions.

Novel Acoustic Scattering Processes for Target Discrimination (2012)

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LONG TERM GOALS

This grant is part of the Shallow-Water Autonomous Sensing Initiative to improve the reliability of acoustic methods using a wide frequency range and scattering data, not necessarily limited to monostatic signatures.

OBJECTIVES

The objective of this grant is to improve the understanding of acoustic scattering processes relevant to man-made objects in the shallow water environment. The current emphasis is on the interpretation of the effects on signatures of placing objects close to an interface. Synthetic aperture sonar, acoustic holographic images, spectral properties of scattering, and bistatic scattering are also examined. Other objectives involve improved understanding and modeling of scattering mechanisms.

APPROACH

A multifaceted research approach appears to be advisable because some acoustic strategies may not *always* be applicable and different strategies may require widely different amounts of time to acquire data for a region of interest. Consequently it appeared to Marston that this project should retain research concerning both low frequency and high frequency sonar technologies. Beginning in FY07, the experimental effort at WSU was shifted to emphasize scaled targets directly relevant to the planning and interpretation of experiments carried out at NSWC-PCD in cooperation with UW-APL. Thus, as explained in the prior reports [1], measurements at WSU were extended to include bistatic and monostatic acoustic properties of solid aluminum cylinders in the free field and adjacent to interfaces. This kind of target was selected because experiments at the NSWC pond have used aluminum cylinders and other objects of various dimensions. Furthermore, scattering by an aluminum cylinder has become a test case for development of finite element methods for the evaluation of both free-field scattering and scattering by targets adjacent to an interface [2-5]. In support of those efforts the experiments at WSU have been concerned with frequency domain ("acoustic color") displays of the scattering as well as time domain and spatial bistatic SAS and holographic imaging displays [4-6]. The features investigated include those that would not be present if it were possible to replace the target by a rigid object. Such features may be referred to as elastic glints.

During FY10 the approaches were broadened to include tests involving inverse imaging based on reversible line-scan SAS (RSAS), reversible circular SAS (RCSAS), and reversible line-scan bistatic quasi-holographic imaging [7-9]. The reversible aspect of these methods makes it feasible to extract the signals and spectral content associated with a designated masked region of an image. Among other applications, this technique makes it possible to test hypotheses concerning the cause of certain image features. New phenomena examined during FY12 are emphasized in this report.

Theoretical components of the research include extensions of prior modeling of scattering amplitudes of objects viewed at grazing incidence [10] and the analysis of aspects of the scattering of acoustic beams [11-15].

Professor P. L. Marston directs the research. During FY12 the graduate students supported at least in part by this grant are listed below together with the nature of their research. These students were: G. Eastland (Franz wave enhancements and scattering by metallic cylinders near flat surfaces and SAS imaging); A. R. Smith (Franz wave enhancements and elastic features visible in SAS imaging); and V. Bollen (experiment setup and beam scattering during summer). Dr. D. B. Thiessen, a WSU Research-Faculty member, assisted with experiment design, FEM computations, and occasional oversight tasks.

WORK COMPLETED

During FY12 Eastland completed his Ph. D. dissertation [16] and various publications appeared, supported partially by this grant [6, 14, 15]. One of those explains our approach to line-scan bistatic quasi-holographic imaging [6]. Work was also published from collaboration on scattering that includes P. Marston [17]. Other selected aspects of the research were presented at meetings of the *Acoustical Society of America* [18-23] and at the *European Conference on Underwater Acoustics* [24, 25].

RESULTS

(1) Franz wave enhancement to the backscattering by slightly exposed metal cylinders (Eastland's investigation): As explained in prior reports, Grant Eastland has been investigating the evolution of the backscattering by solid metal cylinders as they are lowered through a free surface. The cylinder is illuminated broadside at grazing incidence by a short tone burst, typically with a frequency such that ka is between 20 and 25. This type of investigation builds on the prior experiments of Baik and Marston [10] that were carried out with longer tone bursts. Baik's experiments supported a model for describing the scattering by partially exposed cylinders. The new physical mechanism investigated by Eastland is also clearly relevant to understand a scattering by partially-exposed objects even when the surface limiting the exposure is not a free surface [16]. Consequently Eastland's mechanism may be relevant to understanding mechanisms associated with clutter in backscattering, such as the scattering by smooth rocks in sand partially exposed to water and viewed at small grazing angles. Eastland's results and method of analysis are summarized in the following (slightly revised) abstract prepared for presentation [26]: Creeping waves on solid cylinders having slightly subsonic phase velocities and large radiation damping are usually described as Franz waves because of their association with

complex poles investigated by Franz [27]. For free-field high frequency broadside backscattering in water, the associated echoes are weak due to the radiation damping. It is demonstrated here, however, that for partially exposed solid metal cylinders at a free surface viewed at grazing incidence, the Franz wave echo can be large relative to the specular echo even for ka above 20 when the grazing angle is sufficiently small. The reason is that at small grazing angles and small exposures, the Fresnel zone associated with the specular echo is occluded so that the specular echo is weak [10] while the Franz wave is partially reflected at the interface. This has been confirmed from the evolution of echo timing with cylinder exposure and by SAS imaging. In the experiment a solid cylinder was slowly lowered through the free surface into the water. In bistatic scattering a Franz echo can be dominant for small exposures even without the Franz wave having reflected from the free surface for situations where the incident acoustic has reflected from the free surface.

(2) Detection and modeling of the Franz wave reflection (Eastland's monostatic investigation): Figure 1 is an example of one of the results [16]. The envelope of the backscattered signal is recorded and plotted as a function of time when the target is viewed broadside as a grazing incidence. This procedure is repeated as the cylinder is lowered through the free surface. In the plot the signal magnitude is displayed with time along the horizontal axis and the vertical axis showing the amount of exposure, with zero at the top meaning the cylinder has not broken through the surface. The distance shown on the vertical axis is the distance of the lowest part of the cylinder from the free surface. The cylinder diameter is 25.4 mm so that a "Target Depth" of 12.7 mm corresponds to a half-exposed cylinder. The scattering is dominated by the three red loci corresponding to the three paths discussed by Balk and Marston with the earliest one being the direct specular reflection [10]. Since the grazing angle is small (6.3 degrees) the first and later specular reflections are suppressed when the cylinder is less than half exposed. In that case the brightest feature is the delayed response caused by the Franz wave. The solid lines through the early features are the predicted times for the specular mechanisms according to Eastland's extension of the analysis by Balk and Marston [10]. The dashed curve is the predicted arrival time of the Franz wave feature from Eastland's geometric model. The model uses no adjustable parameters when determining the delay relative to the specular features. The Franz wave is partially reflected by the flat surface and the wave reverses its path along the curved surface of the cylinder. An acoustic wave is radiated back to the source at the same location where the Franz wave was launched by the incident acoustic wave.

(3) Franz wave enhancement of the bistatic scattering: Eastland also demonstrated that the same enhancement occurs in the bistatic scattering by a slightly exposed aluminum cylinder at the free surface. In that case he also derived and demonstrated a model for the timing of the Franz wave feature as a function of the amount of exposure of the cylinder. As previously described, the specular reflection loci break up into four loci instead of the three shown in Fig. 1 [28]. As in the monostatic case the Franz wave is partially reflected by the flat surface and the wave reverses its path along the curved surface of the cylinder. In the bistatic case an acoustic wave is radiated to the receiver at a different location from where the Franz wave was launched by the incident acoustic wave.

(4) SAS imaging of Franz wave features: Eastland in his thesis [16] applied the line scan SAS imaging method developed earlier at WSU with assistance from Dr. Timothy M. Marston [8] to the investigation of the aforementioned Franz wave features. The feature was visible on a monostatic as well as bistatic SAS image for slightly exposed cylinders.

(5) Identification of elastic features in SAS images and calculation of feature timing: Eastland in his thesis [16] also modeled and observed in time domain data and in SAS images Rayleigh wave contributions in the backscattering and bistatic scattering by partially exposed aluminum cylinders.

(6) Extension of the range of Franz wave observations in monostatic scattering by partially exposed aluminum cylinders: During summer of 2012, Tony Smith extended the range of grazing angles over which the Franz wave mechanism had been investigated. It was easily observed for grazing angles as large as 60 degrees.

(7) Exact computations of the evolution of backscattering by a rigid cylinder half exposed at a free surface: With the partial support of this grant, Tony Smith obtained additional computational support for Eastland's Franz wave mechanism. Dan Plotnick assisted in this computational effort with support of a different ONR grant. In the relevant plots of the feature timing the vertical axis in Fig. 1 is replaced by the grazing angle as the second variable in addition to the time axis. This computation is summarized in the following (slightly revised) abstract prepared for presentation [29]: Recent observations of the backscattering by partially-exposed solid aluminum cylinders in water viewed at grazing incidence at a free surface [16] indicate that the generation, propagation, and reflection of Franz-type creeping waves can be important. The present investigation gives additional support for this hypothesis by calculating the exact backscattering by a half-exposed infinitely long rigid cylinder viewed over a range of grazing angles. The calculation begins with the known frequency domain expression for the complex amplitude given in an Appendix of [10]. Numerical Fourier transforms were used to construct the time-domain response for various excitations and the evolution of that response was investigated as a function of the grazing angle. This procedure reveals from the timing of the computed features that there is a large delayed echo having the expected timing of a Franz wave partially reflected from the free surface. The timing of the Franz wave depends on grazing angle, in agreement with a geometric model in Eastland's thesis.

(8) Multiple scattering boundary enhancement for a vertically-tilted cylinder: This was detected at WSU for a vertically tilted solid cylinder at a free surface by Plotnick (with some assistance from Bollen) as part of our collaboration with UW-APL and TNO [22].

(9) Modeling of the scattering by targets in acoustic beams: During FY11 Marston and Zhang published several papers on the scattering of sound by spheres placed on the axis of acoustic beams [11-13]. During FY12 they published several additional results. The first of those papers concerns the angular momentum imparted on symmetric objects placed in vortex acoustic fields [14]. One aspect of their analysis extended to the case of non-paraxial beams an expression for the radiation torque derived originally by Hefner

and Marston for paraxial beams [30]. The relation for the torque (topological charge X absorbed power/ ω) was immediately verified experimentally, as discussed in *Physics Today* [31]. Zhang and Marston also proved the same expression for the torque holds even in the case of a standing wave or quasi-standing wave acoustic vortex [14]. The most recent publication [15] concerns the analysis of the asymmetry in the scattering by any object anywhere in a non-diffracting acoustic beam. One aspect of that paper gives an extension of the optical theorem to the case of objects in such beams. Another aspect concerns the relationship between the axial radiation force and the asymmetry of the scattering. Our prior result [13] for a sphere on the axis of a Bessel beam is a special case.

(10) Time reversal measurements for simple targets in the presence of clutter: During FY11 with support from this grant we performed laboratory experiments at WSU on the influence of clutter on mode detection for simple resonant targets in the presence of non-resonant scatterers that served as a source of clutter. Iterative time reversal was successful in pulling out modes in the presence of clutter. Since those experiments were done in cooperation with ONR supported researchers at other facilities, that research will be reported elsewhere. During FY12 Plotnick from, from Marston's group at WSU. participated in related scaled-up experiments at NSWC-PC and at Gulfex-12.

IMPACT/APPLICATIONS

Our SAS and CSAS processing methods have broader applications to data acquisition and object identification. The scattering by objects placed close to a free surface also has plausible implications for understanding other situations of interest. The measured scattering properties of non-axisymmetric targets will eventually find application in the testing of robust FEM scattering codes. Dr. T. Marston has been examining applications at NSWC-PCD of some of the methods developed previously at WSU and/or some of the phenomena previously investigated. Some of the processing methods have been applied to data acquired at NSWC-PCD.

TRANSITIONS

During FY12 Drs. J. R. La Follett and K. Baik, who previously contributed to the project, began research at Shell Development Company (Houston) and KRISS (South Korea), respectively.

RELATED PROJECTS

Some of this work was in cooperation with UW-APL, NSWC-PCD, and TNO.

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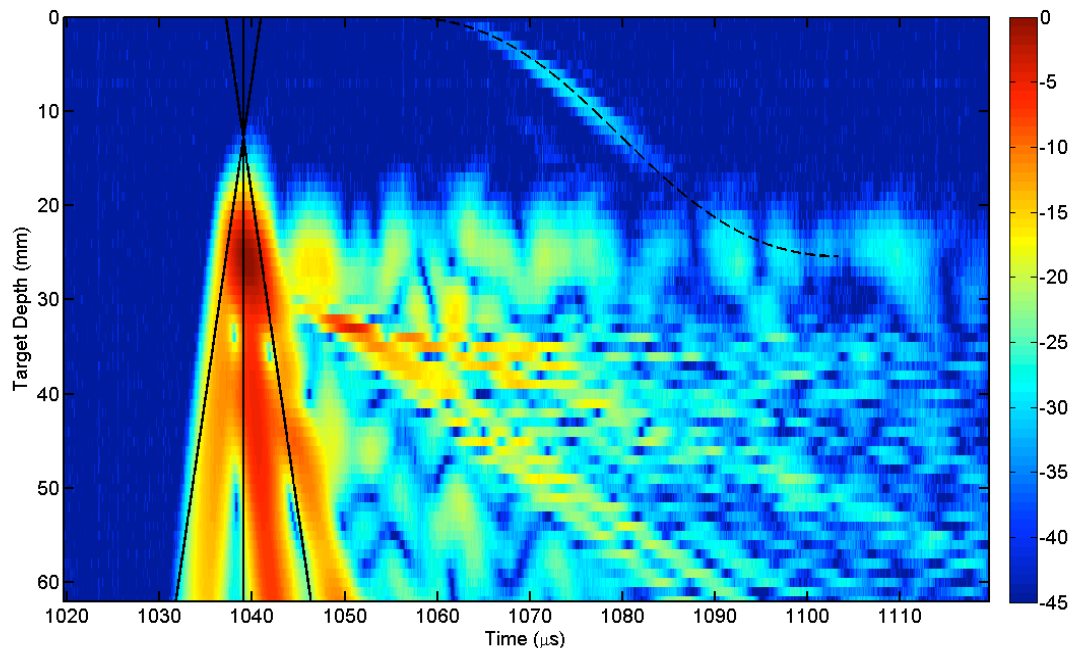


Figure 1. This figure shows the envelope of the grazing monostatic transient response of an aluminum cylinder as a function of target depth relative to the free surface. The cylinder is lowered through the free surface as the broadside monostatic scattering is monitored at a fixed location. The illumination is a one-cycle tone burst at 400 kHz, and the cylinder diameter is 25.4 mm. This record is for a grazing angle of 6.8 degrees. As the cylinder is lowered it becomes exposed to the incident sound. The three solid lines STR, STIR+SITR, & SITIR are the calculated single-scattering specular reflection loci based on a far-field scattering approximation. Those abbreviations indicate the sequence of the reflections in going from the source to the receiver. (Key: S = source, T = target, R = receiver, I = interface.) For example, the earliest locus is for STR, where the acoustic wave is scattered by the cylinder and reaches the receiver without reflecting off the interface. The corresponding specular echoes are weak when the target depth is less than 12 mm because the specular points are not yet exposed when the cylinder is less than 1/2 exposed. When the target depth is less than 12 mm, there is however a stronger delayed echo having an arrival time described by the dashed curve. The cause of that echo is a Franz wave that runs along the surface of the cylinder and is partially reflected at the free surface. The measurements are from Eastland's Ph. D. Thesis.

Novel Acoustic Scattering Processes for Target Discrimination (2013)

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LONG TERM GOALS

This grant is part of the Shallow-Water Autonomous Sensing Initiative to improve the reliability of acoustic methods using a wide frequency range and scattering data, not necessarily limited to monostatic signatures.

OBJECTIVES

The objective of this grant is to improve the understanding of acoustic scattering processes relevant to man-made objects in the shallow water environment. The current emphasis is on the interpretation of the effects on signatures of placing objects close to an interface. Synthetic aperture sonar, acoustic holographic images, spectral properties of scattering, and bistatic scattering are also examined. Other objectives involve improved understanding and modeling of scattering mechanisms for acoustic beams.

APPROACH

A multifaceted research approach appears to be advisable because some acoustic strategies may not *always* be applicable and different strategies may require widely different amounts of time to acquire data for a region of interest. Consequently it appeared to Marston that this project should retain research concerning both low frequency and high frequency sonar technologies. Beginning in FY07, the experimental effort at WSU was shifted to emphasize scaled targets directly relevant to the planning and interpretation of experiments carried out at NSWC-PCD in cooperation with UW-APL. Thus, as explained in the prior reports [1], measurements at WSU were extended to include bistatic and monostatic acoustic properties of solid aluminum cylinders in the free field and adjacent to interfaces. This kind of target was selected because experiments at NSWC have used aluminum cylinders. Furthermore, scattering by an aluminum cylinder has become a test case for development of finite element methods for the evaluation of both free-field scattering and scattering by targets adjacent to an interface [2-6]. In support of those efforts the experiments at WSU have been concerned with frequency domain (“acoustic color”) displays of the scattering as well as time domain and spatial bistatic SAS and holographic imaging displays [3-7]. The features investigated include those that would not be present if it were possible to replace the target by a rigid object. Such features may be referred to as elastic glints. During FY10 the approaches were broadened to include tests involving inverse imaging based on reversible line-scan SAS,

reversible circular SAS, and reversible line-scan bistatic quasi-holographic imaging [8,9]. The reversible aspect of these methods makes it feasible to extract the signals and spectral content associated with a designated masked region of an image. Among other applications, this technique makes it possible to test hypotheses concerning the cause of certain image features. Theoretical components of the research include extensions of prior modeling of scattering amplitudes of objects viewed at grazing incidence [10] and the analysis of aspects of the scattering of acoustic beams. Phenomena examined during FY13 are emphasized in this report.

Professor P. L. Marston directs the research. During FY13 the graduate students supported at least in part by this grant are listed below together with the nature of their research. They are: A. R. Smith (Franz wave enhancements for metal cylinders and related features visible in SAS imaging); V. Bollen (experiment setup and vortex beam scattering experiments); and A. Gunderson (computation of scattering by partially exposed spheres and related Franz wave enhancements and assisting others with experiment setup). Dr. D. B. Thiessen, a WSU Research-Faculty member, assisted with experiment design, FEM computations, and occasional oversight tasks.

WORK COMPLETED

Eastland, who completed his Ph.D dissertation during FY12, prepared during FY13 a manuscript for submission related to his Franz wave discovery [11]. Bollen, who has been experimentally investigating the phase and amplitude structure of the scattering by objects in acoustic vortex beams, published an ICA conference paper summarizing some of his discoveries [12]. A prior WSU graduate student (Dr. L. Zhang) published with Marston an example of how to apply their earlier extension of the optical theorem of objects in acoustic beams [13] to the specific case of a sphere on the axis of an ordinary or vortex Bessel beam [14]. Marston published ICA conference papers analyzing certain viscous corrections relevant to the scattering by small spheres in plane waves and Bessel beams [15] and reviewing earlier research on the time-frequency response of shells [16]. Various results were presented in summary form at ASA or ICA meetings. While not directly supported by ONR, in a spin-off of our prior FEM research Thiessen and Zhang showed how to model capillary wave reflection and transmission using FEM [17].

RESULTS

(1) Franz wave enhancement to the backscattering by slightly exposed metal cylinders (Eastland's investigation): Eastland investigated the evolution of the backscattering by solid metal cylinders as they are lowered through a free surface [6]. The cylinder was illuminated broadside at grazing incidence by a short tone burst, typically with a frequency such that ka is between 20 and 25. Eastland found that for partially exposed solid metal cylinders viewed at grazing incidence, a Franz wave echo can be large relative to the specular echo even for ka above 20 when the grazing angle is sufficiently small. The reason is that at small grazing angles and small exposures, the Fresnel zone associated with the specular echo is occluded so that the specular echo is weak and the Franz wave is partially reflected at the interface. As explained in the manuscript [11] and the FY12 report [18] this has been confirmed from the evolution of echo timing with cylinder exposure. It was also confirmed with SAS imaging [6].

(2) Exact computations of the evolution of backscattering by a rigid cylinder half exposed at a free surface: Smith and Plotnick (who was supported by a different ONR grant) obtained additional computational support for Eastland's Franz wave mechanism. That investigation calculated the exact backscattering by a half-exposed infinitely long rigid cylinder viewed over a range of grazing angles. The calculation used the known frequency domain expression for the complex amplitude given in an Appendix of Baik and Marston [10]. Numerical Fourier transforms were used to construct the time-domain response for various excitations and the evolution of envelope of that response was investigated as a function of the grazing angle as shown in Fig. 1. There is a large delayed echo having the expected timing of a Franz wave partially reflected from the free surface at the shadow side of the cylinder. The timing of the Franz wave depends on grazing angle, in agreement with a geometric model in Eastland's thesis. Other weaker delayed features are present at large angles. These are accounted for with extensions of Eastland's model involving delayed free-surface reflection of the acoustic wave.

(3) Frequency domain features in the backscattering by a rigid cylinder half exposed at a free surface: Baik found that when the amplitude is plotted as a function of the normalized frequency ka for a fixed grazing angle that the slow variations are described using the Kirchhoff approximation [10]. Baik also found, however, fine structure superposed on the exact result that was not predicted by the Kirchhoff approximation. Smith has found from geometric considerations that the fine structure is associated with Franz wave contributions.

(4) Ray-based analysis of Franz wave amplitudes for partially exposed cylinders: As an extension of the numerical approach in (2), Smith and Gunderson have been investigating the quantitative ray interpretation of amplitude information from computational plots of the type shown in Fig. 1. In the ray model it was necessary to introduce a phenomenological Franz wave reflection coefficient. Nevertheless it appears possible to explain certain trends and the rough magnitude using such a ray-based approach. Since the Franz wave is subsonic relative to water modeling the coupling and propagation factors was based on extensions of prior models tested in Marston's group for such waves [19].

(5) Exact scattering for a half-exposed rigid sphere in the frequency domain and in the time domain: Gunderson has also programmed the exact solution for backscattering by a half-exposed rigid sphere at a free surface in a way suitable for evaluating the frequency domain response (analogous to the exact cylinder result plotted in [10]) and the time domain tone burst response (analogous to the cylinder case in Fig. 1). Franz wave contributions are clearly evident in his results in the time domain as well as in the frequency domain. His extraction of the quantitative Franz wave magnitude using this method reveals differences relative to the cylinder-based case which are to be expected from considering the shape of the associated wavefront. In the frequency domain he plotted the rigid surface case also and Franz waves are even more important in that case.

(6) Kirchhoff approximation for spheres partially exposed at a flat surface: In prior research Baik and Marston analyzed the Kirchhoff approximation for a rigid sphere breaking through a free surface and a rigid flat surface [10]. Marston and Smith showed that they could recover the prior results using one-dimensional numerical integration. During FY13, Gunderson formulated the more difficult task of the two-dimensional numerical integration needed for the Kirchhoff approximation for the backscattering by a partially exposed rigid sphere. In the terminology of [10], Gunderson has numerically evaluated the path 0, path 1, and path 2 contribution integrals in the sphere case. This approach will give insight into the relative magnitude of those contributions as a function of grazing angle and phase. He confirmed his formulation by comparison with the exact half exposed partial wave series solution.

(7) High frequency scattering by partially exposed metal cylinders in sand: During FY13 Smith added a sand box to the floor of the small water tank used in Eastland's experiments and began studying the high frequency backscattering by aluminum and stainless steel cylinders for various grazing angles and various amounts of partial exposure. It appeared desirable to determine if the aforementioned Franz wave reflection mechanism is observable in such high frequency scattering for cylinders in sand partially exposed to sound in water at various grazing angles. (To reduce the contamination associated with the possibility of bubbles trapped in the sand, the sand is initially wetted with degassed water at reduced pressure in a separate tank.) Smith has found that the Franz wave effect is observable provided the sand is sufficiently smooth. He has also found that he can significantly enhance the magnitude of the Franz wave reflection by placing a thin metal plate at the location in the shadow of the cylinder where the Franz wave is believed to be partially reflected by the sand. He has viewed the Franz wave contribution using SAS imaging and has also modeled the timing of certain elastic wave contributions to the backscattering.

(8) Phase and amplitude structure in the scattering by small objects in an acoustic vortex beam: The original experiments in vortex beam generation at WSU by Hefner and Marston suggested that such beams could be used for alignment purposes [20]. Developments during the past decade by various other groups have suggested a more diverse range of applications which include sub-wavelength resolution imaging. Bollen has resumed experiments at WSU with vortex beams. He is using a transducer configured in such a way as to generate higher quality vortex beams. In one form of the experiment a sphere is raster scanned through the beam as the scattering is recorded. Initial results concerned measurements of the near-forward scattering by the sphere. That experiment demonstrated that for a first-order vortex beam, the helicity-neutral form of the scattering has the phase structure of a first order vortex while the cross-helicity form is that of a second-order vortex. Those results agree with our predictions though we believe there have been no prior investigations of the cross-helicity scattering. The cross helicity result [12] is shown in Fig. 2. Bollen is now studying near-backward scattering.

(9) Modeling of the scattering by targets in acoustic beams: During FY13 Zhang and Marston published an analysis of how to apply their extended optical theorem for beams [13] to the case of a sphere in a Bessel beam [14]. Marston analyzed the effects of

viscous dissipation on the scattering by small spheres for the case of spheres in plane waves or in Bessel beams [15]. Both of the publications in 2013 included regular zero-order Bessel beams as well as vortex Bessel beams. One aspect of our prior research concerns the existence of negative radiation forces demonstrated in 2013 [21].

IMPACT/APPLICATIONS

Our SAS and CSAS processing methods have broader applications to data acquisition and object identification. The scattering by objects placed close to a free surface also has plausible implications for understanding other situations of interest. Our research into backscattering by partially exposed smooth hard objects should eventually prove relevant to the modeling of clutter signals associated with partially exposed smooth rocks in sand. Our research into the scattering by vortex beams should be eventually useful for alignment purposes and may prove useful for sub-wavelength resolution imaging and long-range propagation because of the robust nature of topological wavefield properties.

RELATED PROJECTS

Some of this work was in cooperation with UW-APL and NSWC-PCD. The notched cylindrical aluminum target designed and fabricated at WSU with support from this grant has remained useful as a test target at NSWC-PCD [22].

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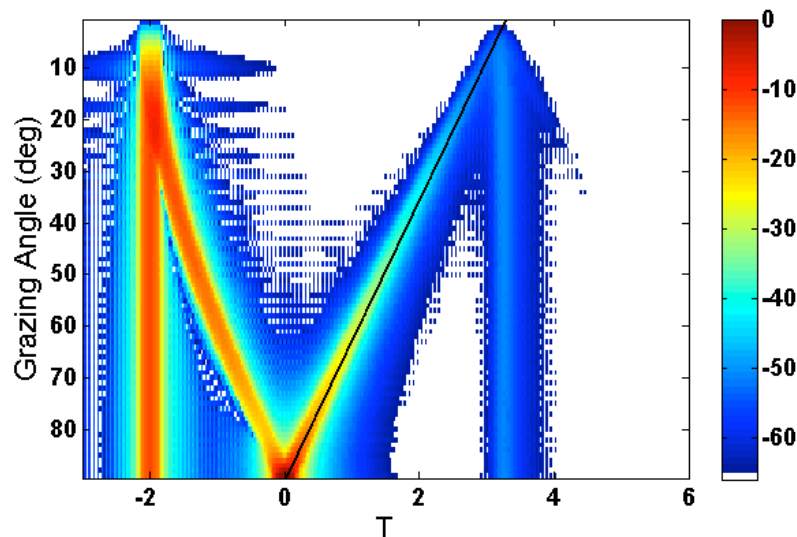


Figure 1. This figure shows the envelope of the monostatic tone burst response of a half exposed rigid cylinder as a function of grazing angle. The horizontal axis is dimensionless time $T = ct/a$ where c is the speed of sound in water, a is the cylinder radius, and t is the time. The color-bar shown on the right is a dB scale. The cylinder is at free surface and the broadside monostatic scattering is computed using an exact partial wave series. The tone burst response is synthesized using Fourier superposition. The echo at $T = -2$ is the direct specular reflection. All echoes with $T > 0$ are Franz wave echoes; the earliest is along the solid line computed from ray theory. The tone burst frequency has $ka = 21.5$ and the duration of the incident burst is one cycle.

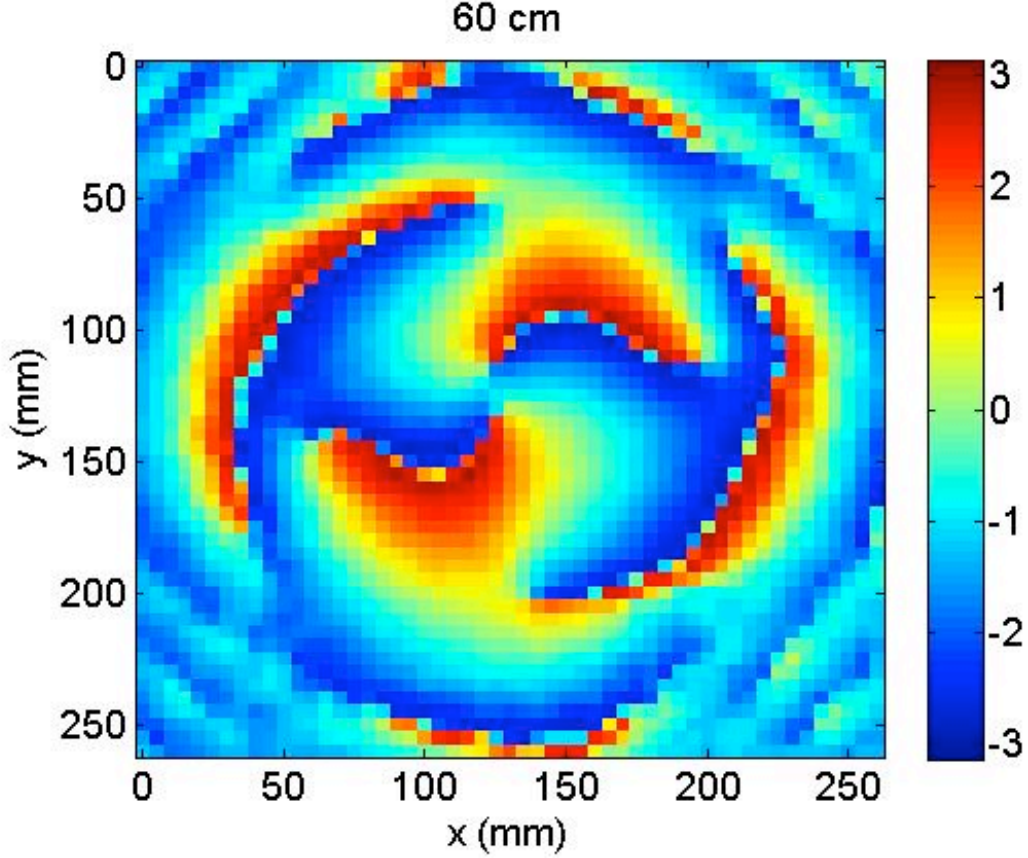


Figure 2. Instantaneous phase of the receiver array output is shown when the array is set in the configuration favoring cross-helicity detection of scattering relative to the incident first-order vortex beam. The horizontal and vertical axes give the horizontal and vertical coordinate of the center of a sphere scanned through the beam in a plane 60 cm from the source. The phase, in radians, is given by the color-bar shown on the right. The displacements of the sphere are measured in mm. Near the center of the pattern, the sphere is very close to the axis of the incident beam; the received amplitude is weak and the phase is indeterminate. When the sphere is displaced from the axis of the beam, while in the proximity of the axis, the phase of the array output evolves similar to a second-order beam since there are two ridges (red) in the inner swirl. The increase in phase-order is a new effect and is supported by theory we developed.

Novel Acoustic Scattering Processes for Target Discrimination (2014)

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LONG TERM GOALS

This grant is part of the Shallow-Water Autonomous Sensing Initiative to improve the reliability of acoustic methods using a wide frequency range and scattering data, not necessarily limited to monostatic signatures.

OBJECTIVES

The objective of this grant is to improve the understanding of acoustic scattering processes relevant to man-made objects in the shallow water environment. The current emphasis is on the effects on signatures when objects are placed close to an interface. Synthetic aperture sonar, acoustic holographic images, spectral properties of scattering, and bistatic scattering are also examined. Other objectives involve improved understanding and modeling of scattering mechanisms for acoustic beams.

APPROACH

A multifaceted research approach appears to be advisable because some acoustic strategies may not *always* be applicable and different strategies may require widely different amounts of time to acquire data for a region of interest. Consequently it appeared to Marston that this project should retain research concerning both low frequency and high frequency sonar technologies. Beginning in FY07, the experimental effort at WSU was shifted to emphasize scaled targets directly relevant to the planning and interpretation of experiments carried out at NSWC-PCD in cooperation with UW-APL. Thus, as explained in the prior reports [1], measurements at WSU were extended to include bistatic and monostatic acoustic properties of solid aluminum cylinders in the free field and adjacent to interfaces. This kind of target was selected because experiments at NSWC have used aluminum cylinders. Furthermore, scattering by an aluminum cylinder has become a test case for development of finite element methods for the evaluation of both free-field scattering and scattering by targets adjacent to an interface [2-6]. In support of those efforts the experiments at WSU have been concerned with frequency domain (“acoustic color”) displays of the scattering as well as time domain and spatial bistatic SAS and holographic imaging displays [3-7]. The features investigated include those that would not be present if it were possible to replace the target by a rigid object.

Such features may be referred to as elastic glints. During FY10 the approaches were broadened to include tests involving inverse imaging based on reversible line-scan SAS, reversible circular SAS, and reversible line-scan bistatic quasi-holographic imaging [8,9]. The reversible aspect of these methods makes it feasible to extract the signals and spectral content associated with a designated masked region of an image. Among other applications, this technique makes it possible to test hypotheses concerning the cause of certain image features. Theoretical components of the research include extensions of prior modeling of scattering amplitudes of objects viewed at grazing incidence [10] and the analysis of aspects of the scattering of acoustic beams. Phenomena examined during FY14 are emphasized in this report.

Professor P. L. Marston directs the research. During FY14 the main graduate students supported at least in part by this grant are listed below together with the nature of their research. They are: A. R. Smith (Franz wave enhancements for metal cylinders partially buried in sand); V. Bollen (experiment setup and vortex beam scattering experiments); and A. Gunderson (computation of scattering by partially exposed spheres and related Franz wave enhancements and assisting others with experiment setup).

WORK COMPLETED

Eastland, who completed his Ph.D dissertation during FY12, published during FY14 a manuscript on his discovery of Franz wave backscattering enhancements for cylinders partially exposed at a free surface [11]. Smith confirmed Franz wave backscattering enhancements are also present for cylinders partially exposed in sand. He also completed his Ph. D. thesis [12]. Bollen, who has been experimentally investigating the phase and amplitude structure of the scattering by objects in acoustic vortex beams, improved his backscattering experiments. He also improved the positioning system needed for those experiments and for SAS experiments. Research concerning partially exposed targets associated with a prior grant was submitted and accepted for publication [13]. For Gunderson's work, see the report for grant N000141210044.

RESULTS

(1) Franz wave enhancement to the backscattering by slightly exposed metal cylinders (Eastland's investigation): Eastland found that for partially exposed solid metal cylinders viewed at sufficiently small grazing incidence, a Franz wave echo can be large relative to the specular echo even for ka above 20 when the grazing angle is sufficiently small. The reason is that at small grazing angles and small exposures, the Fresnel zone associated with the specular echo is occluded so that the specular echo is weak and the Franz wave is partially reflected at the interface behind the cylinder [11]. The partial reflection of the Franz wave is a form of multiple scattering since in effect the wave goes from the target to the interface and back to the target. Supporting computational research by Smith, Plotnick, and Gunderson summarized in the report for FY13 need not be repeated here. As reported in the FY14 report for N000141210044, Gunderson has demonstrated that Franz wave backscattering enhancements similar to those reported by Eastland [11] are also present when spheres and smooth stones are lowered through a free surface.

(2) High frequency scattering by partially exposed metal cylinders in sand: During FY13 Smith added a sand box to the floor of the small water tank used in Eastland's experiments and began studying the high frequency backscattering by aluminum and stainless steel cylinders for various grazing angles and various amounts of partial exposure. The sand was saturated with water. During FY14 Smith verified that the aforementioned Franz wave reflection mechanism is observable in high frequency scattering for cylinders in sand partially exposed to sound in water at various grazing angles (determined by the relative positions of the transducer and the cylinder) [12]. Figure 1 shows an example of measurements taken for a partially exposed aluminum cylinder viewed over a range of grazing angles. The cylinder is illuminated by a short tone burst so that different scattering mechanisms are separated in time in the received signal. The locus of the envelope of the received signals is plotted as a function of the grazing angle and the locus can be compared with loci computed for different scattering mechanisms. Typically an early echo is directly from the line where the cylinder contacts the sand on the illuminated side of the cylinder. (In a few cases there is an earlier specular reflection off of the cylinder by a wave refracted through the sand, but in most cases that is weak because of attenuation in the sand for the frequencies used, typically near 400 kHz.) Smith has found that the Franz wave effect is observable ordinarily when the sand is sufficiently smooth. He found that the Franz wave contribution is usually strengthened by placing a thin brass plate on the sand in contact with the cylinder on the cylinder's backside. As a consequence of the plate's inertia the reflection coefficient increases and that increase usually strengthens the Franz wave backscattering contributions. Notice, however, that even without the plate the Franz wave contribution is significant when the cylinder is more than half buried.

(3) Other high-frequency scattering mechanisms for solid metal cylinders partially buried in sand and viewed at grazing incidence: Smith studied other timing loci for the received backscattering as a function of the grazing angle. The associated mechanisms can include [12]: (a) as previously mentioned, a specular reflection off of the cylinder by a wave refracted through the sand -- the evolution of the timing of that contribution relative to the direct contribution from the contact line for a slightly exposed cylinder is useful for determining the speed of longitudinal wave propagation in the saturated sand; (b) a Rayleigh-like wave on the cylinder which couples to longitudinal waves in the sand as well as to sound waves in water -- and hence has asymmetric coupling angles because of the different sound speeds; (c) a Rayleigh – Franz wave hybrid corresponding to a wave which mode converts from one type to the other where the cylinder contacts the sand on the back side. These processes illustrate the complexity of high-frequency backscattering mechanisms for partially exposed targets.

(4) Phase and amplitude structure in the scattering by small objects in an acoustic vortex beam: The original experiments in vortex beam generation at WSU by Hefner and Marston suggested that such beams could be used for alignment purposes [14]. Developments during the past decade by various other groups have suggested a more diverse range of applications that include sub-wavelength resolution imaging. As explained in the report for FY13, Bollen resumed experiments at WSU with vortex beams. He is using a transducer configured in such a way as to generate higher quality

vortex beams. In one form of the experiment a sphere is raster scanned through the beam as the scattering is recorded. The experiments summarized in the FY13 report and in [15] concerned measurements of the near-forward scattering by the sphere. Bollen's research during FY14 emphasized the near-backward scattering using an improved apparatus. That experiment demonstrated that for a first-order vortex beam, the helicity-neutral form of the backscattering has the phase structure of a first order vortex while the cross-helicity form is that of a second-order vortex as was also found for the forward scattering case [15]. Figure 2 shows an example of helicity-neutral detection. The extreme sensitivity of the detected signal when the scatterer is positioned near the vortex core may have applications in alignment and high-resolution imaging. The co-helicity component was also measured. This set of observations display newly observed phase patterns.

(5) Modeling of the scattering by targets in acoustic beams and at interfaces: During FY14 Marston published an analysis of how an extended optical theorem applies to certain objects in beams [16]. The basic theorem was previously given by Zhang and Marston [17] and also applies to objects in waveguides. Some prior ONR supported research by Baik was submitted and accepted [13].

(6) Review presentations: Marston prepared invited reviews for the ASA Providence meeting pertaining to prior ONR supported research [18,19].

IMPACT/APPLICATIONS

Our SAS and CSAS processing methods have broader applications to data acquisition and object identification. The scattering by objects placed close to a free surface also has plausible implications for understanding other situations of interest. Both the Franz wave backscattering enhancement [6,11,12] and some other effects observed by Eastland [6] are examples of multiple single-target interactions with acoustic waves. Our research into backscattering by partially exposed smooth hard objects should eventually prove relevant to the modeling of clutter signals associated with partially exposed smooth rocks in sand. Our research into the scattering by vortex beams should be eventually useful for alignment purposes and may prove useful for sub-wavelength resolution imaging and long-range propagation because of the robust nature of topological wavefield properties.

RELATED PROJECTS

Some of this work was in cooperation with UW-APL and NSWC-PCD. The notched solid cylindrical aluminum target designed and fabricated at WSU with support from this grant has remained useful as a test target in the BayEx14 experiments and an additional small solid target fabricated at WSU during FY14 was also deployed there..

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PUBLICATIONS

G. E. Eastland & P. L. Marston, “Enhanced backscattering in water by partially-exposed cylinders at free surfaces associated with an acoustic Franz wave,” J. Acoust. Soc. Am. 135, 2489-2492 (2014) [published, refereed].

A. R. Smith, *Acoustic scattering enhancement for partially-exposed cylinders in sand and at a free surface caused by Franz waves and other processes* (Ph. D. Thesis, Washington State University, Pullman, WA, 2014).

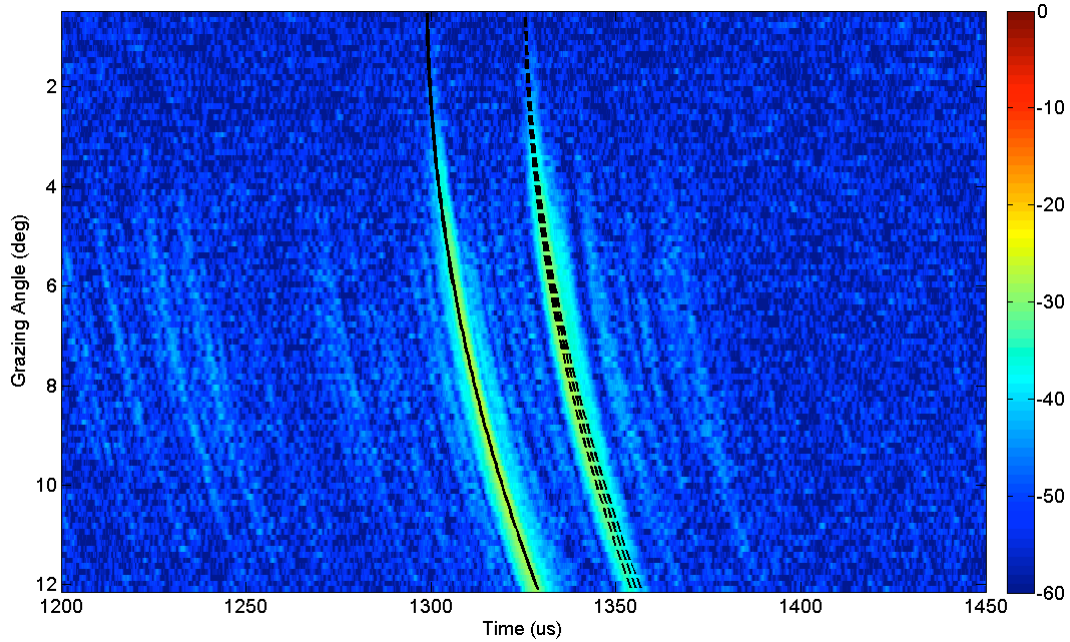


Figure 1. This figure shows the envelope of the monostatic tone burst response of a one-eighth exposed aluminum cylinder in sand (viewed broadside) as a function of time and of grazing angle. The tone burst frequency is such that $ka = 25.7$ and the duration of the source excitation is one cycle. The horizontal axis is the round-trip propagation time in microseconds. The vertical axis is the grazing angle in degrees. The color-bar shown on the right is a dB scale. The solid curve superposed on the earliest significant arrival is the computed locus of the direct arrival. The three dashed curves superposed on the later bright arrival are predicted arrival times of three superposed Franz wave contributions. The figure shows that the Franz wave contributions are significant for small grazing angles.

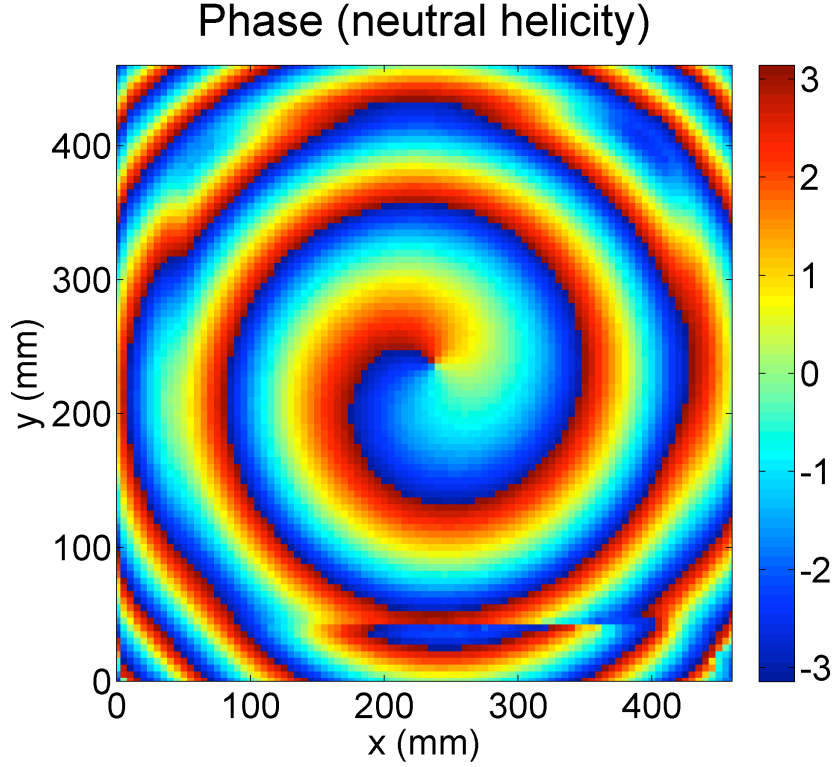


Figure 2. Instantaneous phase of the receiver array output is shown when the array is set in the configuration for helicity-neutral detection of backscattering by a sphere raster scanned in a first-order vortex acoustic beam. The horizontal and vertical axes give the horizontal and vertical coordinate of the center of a sphere scanned through the beam. The phase, in radians, is given by the color-bar shown on the right. The displacements of the sphere are measured in mm. Near the center of the pattern, the sphere is very close to the axis of the incident beam; the received amplitude is weak and the phase becomes indeterminate though it changes rapidly with position near the center of the vortex. When the sphere is displaced from the axis of the beam, while in the proximity of the axis, the phase of the array output evolves similar to a first-order beam since there is one ridge (red) in the inner swirl of the spiral. The phase evolution is supported by theory we developed.

V. Abstract of Grant C. Eastland's Ph.D. dissertation (2012).

ACOUSTICAL SCATTERING FROM CYLINDERS AND OTHER OBJECTS: SHORT-PULSE SIGNATURES, BISTATIC SYNTHETIC APERTURE AND HOLOGRAPHIC IMAGING, AND INTERFACIAL SCATTERING CONTRIBUTIONS, Ph. D. dissertation (Washington State University, Pullman, WA, August 2012).

Abstract: In the present investigation, partial exposure was studied by lowering a solid aluminum cylinder through a flat free surface into a tank of water while monitoring the evolution of the scattering as a function of the amount of exposure. Understanding scattering features of cylinders for several different exposures (h/a) is relevant to the scattering by a variety of simple targets. Interactions with the free surface simulate aspects of interactions with flat sediment. Work in both monostatic and bistatic scattering and reversible filtering is used, which is based on a form of synthetic aperture sonar (SAS). The source and receiver grazing angles are held fixed while the amount of exposure of a right circular aluminum cylinder is varied. Short pulses are used to distinguish between different types of scattering contributions. The slope of the feature timing as a function of the target depth h , expressed by the derivative dt/dh where t is the measured time of the feature, depends on the feature type as well as the source and receiver grazing angles. Free surface interactions for features revealed by the slope dt/dh are consistent with feature identification using reversible SAS filtering. The presence of the interface contributes many more paths for scattering to occur, even with the case of broadside illumination considered. Utilizing this information, ray theoretic methods were used to develop absolute time models for the various mechanisms. Three different domains were used in this investigation: target-depth versus time, receiver-depth versus time and SAS image domains.

Reversible SAS filtering of monostatic and bistatic data is used to identify different specular mechanisms involving the target and free surface, in addition to the corresponding elastic responses. Delayed multiple scattering features are also visible involving more than one reflection from the target. During the investigation, additional mechanisms were discovered and studied: Franz wave features, which are from diffracted acoustic surface waves and Rayleigh wave features, which are Surface Elastic Waves.

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VI. Abstract of Anthony R. Smith's Ph.D. Dissertation (2014)

ACOUSTIC SCATTERING ENHANCEMENT FOR PARTIALLY-EXPOSED CYLINDERS IN SAND AND AT A FREE SURFACE CAUSED BY FRANZ WAVES AND OTHER PROCESSES, Ph. D. dissertation (Washington State University, Pullman, WA, August 2014).

Abstract: Franz waves are a family of creeping subsonic acoustic waves that travel along curved surfaces of solid stiff objects in water. When such objects are not located near the boundaries of the water, Franz waves usually contribute only weakly to high-frequency backscattering in comparison with simple reflection from the object. It was recently demonstrated, however, that for partially-exposed solid metal cylinders at a free surface viewed at grazing incidence, the Franz wave echo can be large relative to the specular echo when the grazing angle is sufficiently small [G. C. Eastland and P. L. Marston, J. Acoust. Soc. Am. 135, 2489-2492 (2014)]. The Franz wave is partially reflected where the free surface contacts the cylinder's backside. The research presented here gives theoretical, computational, and experimental extensions of that work.

The exact partial-wave series for scattering from an infinitely-long, rigid circular cylinder half-exposed at a free surface, was converted from the frequency domain to the time domain, which revealed three scattering features which matched the timing of Franz waves. The three features correspond to the three possible paths a Franz wave can take along a cylinder, reflecting off the surface in front of the cylinder zero, one, or two times.

The experimental emphasis concerns analogous Franz wave high-frequency echoes for cylinders partially buried in sand. Sand was degassed and transferred to a sandbox in a water tank. Stainless-steel and aluminum cylinders were buried with various exposures in the sandbox. Vertical transducer scans revealed refracted rays into the sand, and a numerical method was used to plot timing curves to these features and thus empirically determine the sand's sound speed. Scans for each cylinder at one-eighth, one-fourth, and one-half exposure confirmed that Franz waves were present. The Franz echoes were generally stronger for lower exposure, and were often enhanced by the placement of a brass plate behind the cylinders for stronger reflection.

Transducer scans with the aluminum cylinder at the air-water interface showed the presence of Franz waves, which were stronger for lower exposure. Vertical scans of the cylinder at the interface for various grazing angles also showed Franz echoes.

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